The Diverse Mesoscopic Structures in Rapakivi Granites of Southeastern Finland

Episyenites and related processes

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ACADEMIC DISSERTATION
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Abstract

Peralkaline syenites and granites form a small yet significant group of rocks within the A-type granite association worldwide. Although the Mid-Proterozoic Finnish rapakivi (A-type) granite complexes are voluminous in southern Finland, they only host minor quantities of peralkaline and marginally metaluminous syenitic rocks. Within the southeastern part of the subalkaline 1644-Ma Suomenniemi rapakivi granite complex (SE Finland), these alkali-feldspar rich syenitic rocks form numerous NW-oriented dike- and pod-like bodies, up to 5 meters in width and 100 meters in length. The Suomenniemi complex is thought to have formed by melting of granodioritic lower crust, whereas peralkaline syenites generally form by melting or fractionation of alkaline and transitional basalts, sourced in the subcontinental lithospheric mantle. Because of extensive fractionation and significant late fluid processes, peralkaline rocks are often associated with important mineralization. The origin and ore-forming potential of these rocks were studied using isotope geochemistry (single-grain zircon U-Pb and O, whole-rock Sm-Nd), mineral chemistry, whole-rock geochemistry, optical petrography and cathodoluminescence petrography. The data imply that these syenitic rocks formed in situ from the rapakivi granite either in post-magmatic (episyenites) or late-magmatic stage in the presence of a sodic fluid, and do not require a distinct magmatic source. Varying temperatures and differing fluid compositions produced geochemically and mineralogically diverse syenitic rocks, connected by relatively sodic and oxidized mineralogy and significant Si-depletion. The mechanism for the loss of Si from the rapakivi granite (or granite magma) is an elusive issue. In some, if not all, of the syenitic rocks it likely results from quartz dissolution and transport (episyenitization) after the transition from lithostatic to hydrostatically pressurized magmatic-hydrothermal system. Some of the syenitic rocks include hypersolvus feldspar and record ductile deformation, suggesting relatively high alteration temperature and pressure; if these rocks did not form in the subsolidus, a late-magmatic filter-pressing process during magmatic shearing resulted in loss of interstitial Si-rich magma and caused accumulation of K-feldspar. The ambiguous (magmatic/post-magmatic) textures of these rocks emphasize the nontrivial distinction between magmatic and (high-temperature) metasomatic processes. While episyenites are related to significant uranium and tin deposits worldwide, the economic potential of the syenitic rocks found in the Suomenniemi complex area is probably insignificant. The possible occurrence of these rocks beyond the Suomenniemi rapakivi complex, as well as the exact timing of alteration, should be constrained by further field work and radiogenic isotope dating.

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Contents

List of original publications

This thesis is based on the following publications:

I Suikkanen, E., Rämö, O.T., 2017, Metasomatic alkali-feldspar syenites (episyenites) of the Proterozoic Suomenniemi rapakivi granite complex, southeastern Finland. Lithos 294–295, 1–19. doi: 10.1016/j.lithos.2017.09.017

II Suikkanen, E., Rämö, O.T., Ahtola, T., Lintinen, P., 2019, Clinopyroxene episyenites in a Proterozoic rapakivi granite, SE Finland — recrystallization textures, mass transfer and implications for the petrology of A-type granite complexes. Mineralogy and Petrology 113, 727–743. doi: 10.1007/s00710-019-00684-w

III Suikkanen, E., Rämö, O.T., 2019, Episyenites—characteristics, genetic constraints and mineral potential. Mining, Metallurgy & Exploration 36, 861–878. doi: 10.1007/s42461-019-00120-9

The publications are referred to in the text by their roman numerals.

Authors' contribution to the publications

I ES and OTR: Design of the study. OTR: Project funding, Sm-Nd and Rb-Sr analyses, writing Sm-Nd and Rb-Sr results and editing the manuscript. ES: Zircon sample preparation, zircon U-Pb and O SIMS analyses, microprobe analyses, optical petrography, cathodoluminescence imaging, data reduction and figures, interpretation of the data.

II ES and OTR: Design of the study. ES: Sampling of drill core, microprobe analyses, XRF-analyses, reduction of microprobe data and geochemical data, mass balance modeling, figures, interpretation of the results and writing the manuscript. OTR: Project funding. TA and PL: Planning and execution of drilling operation. TA: Drill core logging. OTR, TA and PL: Editing the manuscript.

III ES: Design of the study, solubility calculations, figures and writing. OTR: Project funding, editing the manuscript.

1 Introduction

Deep in the continental crust, igneous differentiation, metamorphism, deformation and hydrothermal processes, among others, have shaped the rocks seen on the Earth's surface today. These processes lead to formation of diverse mesoscopic heterogeneities in rocks, including dikes, joints, shear zones and hydrothermal and metasomatic veins. These localized anomalies are interesting from the petrological and ore-geological points of view, both shaping our understanding of evolution of the Earth's crust, and potentially hosting important mineralization. This thesis describes an occurrence of episyenites, a type of syenitic rocks formed via hydrothermal alteration, recognized for the first time from the rapakivi granites of southeastern Finland.

1.1 Rapakivi granites and peralkaline rocks

During the Svecofennian orogeny at 1.92–1.82 Ga, the building blocks of the Svecofennian crust accreted against the Archean core of the Fennoscandian shield (Lahtinen et al. 2005). The roots of the Svecofennian composite orogen are now visible in southwestern Finland as granite intrusions surrounded by migmatizing metasedimentary rocks and metavolcanic belts. At ~1.645 Ga, ca. 175 Ma years after the end of the Svecofennian orogeny, the thickened orogenic crust in the area of southern Finland entered an extensional stage. The extension was associated with mafic underplating, which resulted in intrusion of basaltic dike swarms as well as in melting of the lower crust to form large bodies of A-type granite (Haapala and Rämö 1990; Heinonen et al. 2010). The largest of these A-type granite bodies, the Wiborg batholith in southeastern Finland, is well known due to the widespread occurrence of the rapakivi texture, which famously comprises K-feldspar phenocrysts surrounded by rims of plagioclase. These type of granites are globally known as rapakivi granites (Rämö and Haapala 1995).

The 1644 Ma Suomenniemi rapakivi granite complex, SE Finland, is the oldest of the Finnish rapakivi granite intrusions (Rämö and Mänttäri 2015), emplaced ca. 15 m.y. before the giant Wiborg rapakivi granite batholith to the south (Heinonen et al. 2016). The Suomenniemi complex comprises amphibole granite, biotite granite and topaz-bearing biotite granites that form a fractionation series following the emplacement of a common granodiorite-derived parent magma. The bimodal magmatism typical of A-type granite complexes is displayed by the swarm of SW-striking basaltic dikes, some of which cut the granites of the Suomenniemi complex (Rämö 1991). In addition, dike-like bodies of metaluminous to peralkaline alkali-feldspar syenitic rocks have also been described from the Suomenniemi complex, being the only occurrence of peralkaline rocks within the Finnish rapakivi granites.

Although minor constituents of the continental crust, peralkaline rocks are interesting from ore geologic and petrologic points of view. Due to peralkaline chemistry, i.e. having agpaitic index [AI: molar ratio (Na+K)/Al] of more than one, all Na or K do not fit into the structure of crystallizing feldspar, which leads to characteristic formation of alkali-rich pyroxene or amphibole. Peralkaline syenites are commonly thought to form by melting or extensive fractionation of alkaline and transitional basalts, sourced in the subcontinental mantle (Frost and Frost 2008; Litvinovsky et al. 2015). Rocks with peralkaline chemistry and/or mineralogy may also form by fenitization-type metasomatic alteration around alkaline–carbonatite intrusions (Le Bas 1987) and in hydrothermal circulation cells within the upper crust (Cuney et al. 2012). Whether

magmatic or metasomatic, these rocks are commonly associated with continental rifting and thus their association to A-type granites is not unusual. In addition, extensive fractional crystallization and/or hydrothermal processes related to A-type or peralkaline magmatism and crustal metasomatism may lead to enrichment of metals, such as the REE and Sn.

The syenitic rocks of the Suomenniemi complex were initially briefly described as igneous dykes related to the rapakivi granite magmas (Rämö 1991), but (prior to this thesis) no extensive scientific analysis concerning their origin has been conducted, and the relationship between these peralkaline rocks and the rapakivi granites has thus been largely unknown. As the crustal source assumed for the rapakivi granite of southeastern Finland is not typical of peralkaline rocks, their genesis and metallogenic potential was studied in this thesis. Post-magmatic metasomatism and quartz-depletion (episyenitization) are also important processes that may lead to formation of diverse syenitic rocks. The importance of these processes (as described below) is the major implication of the thesis.

1.2 Metasomatism

Metasomatism, or fluid-mediated replacement of mineral with another of a different composition, is a well-established process with major petrological and ore-geological significance in magmatic–hydrothermal and metamorphic environments. Saline fluids with Na, Ca, K, Mg and/or Fe may react strongly with rocks and metasomatism may lead to complete consumption of original rock-forming minerals. In the continental crust, metasomatism forms localized features in brittle-to ductile shear zones, as well as regional features such as albitization (Boulvais et al. 2007) and fenitization (Le Bas 1987). The permeability of rocks is enhanced by fracturing (including microfracturing) and porosity resulting from recrystallization (e.g. Fusseis et al. 2009) and mineral replacement via coupled dissolution and reprecipitation (Putnis 2002). Generation of nanoscale porosity during metasomatism has a negative effect on rock strength, promoting fracturing and again increasing porosity and fluid flow.

In cases where permeability (and fluid velocity) is sufficient and fluid properties are suitable, leaching of minerals is possible. In rare cases, the fluid flowing through fractures in granitic rock is Si-undersaturated, leading to leaching of quartz and resulting in formation of quartz-depleted syenitic rocks—episyenites. Episyenitization can increase permeability significantly amplifying metasomatic alteration within and around the fluid conduit. Together the hydrothermal processes, leaching and metasomatism, may lead to significant mass transfer and concentration of elements into suitable upper crustal sinks, including the porous feldspathic husks left behind by episyenitization.

1.3 Episyenitization

The term episyenite was first used by the French mineralogist Alfred Lacroix (1920) to describe, from the French Pyrenees, epigenetic syenites whose protolith (the precursor rock) could not be identified with certainty. Lacroix (1920) suggested that the protolith was berondrite, a variety of nepheline pyroxenite, common in the area and thus these epigenetic syenites were formed due to metasomatic addition of Si and Al, and replacement of nepheline with alkali feldspar. While this original definition of episyenite does not constrain the mineralogy of the protolith, the term was later adopted by French ore geologists and miners to describe quartz-depleted and uranium mineralized rocks from the Variscan granite massifs in France. The

economic prospects of these rocks as well as the developments in relevant research methods increased the interest and opportunities to study their formation and produced a body of scientific literature in the latter half of the 20th century. The research combined mineralogical, geochemical and fluid inclusion studies to constrain the timing of quartz-depletion and associated alkali metasomatism, composition and sources of fluids associated to quartz-depletion and mineralization in episyenites (e.g. Leroy 1978). Because of these studies, in modern geology the term episyenite is invariably connected to dissolution of quartz. English literature episyenitization was rare before the classic review of episyenites from the French Massif Central by Cathelineau (1986). Since then, the term episyenite has been connected to many occurrences of metasomatized, quartz-depleted rocks from all over the world, including both barren (Petersson and Eliasson 1997; this study) and U-, Sn-, or Au-mineralized variants (e.g. Charoy and Pollard 1989; López-Moro et al. 2013; Patrier et al. 1997). As no official definition of the term 'episyenite' exists, a wide mineralogical variety of episyenite have been described, formed in varying conditions. In the future, it is important to define and constrain the term along with other related terms commonly used for metasomatized rocks, as unified nomenclature is the key in understanding significance and scope of geological processes.

2 Research questions

The primary objective of this thesis is to describe the petrogenesis of the varying peralkaline and peraluminous rocks found within the Suomenniemi rapakivi granite complex. Specific objectives of the thesis included: (1) Describing the mineralogy and texture of the rocks by standard optical microscope study, cathodoluminescence microscopy, and electron microprobe analysis; (2) Obtaining U-Pb- and O-isotopic data from zircon, as well as whole-rock Sm-Nd data to understand the connection of the rocks with the ca. 1640-Ma anorogenic magmatism in SE Finland; and (3) Geochemical characterization of the rocks.

Mainly due to China controlling the rare earth element (REE) market, the political will in the Western world has shifted its focus on the possibility of future self-sustainability with the respect to production of the REE and other "critical" metals important to modern industry. As a part of this movement, the Critical Minerals project of the Geological Survey of Finland (GTK) (1.1.2016–31.12.2018) aimed at discovering and cataloging the Finnish REE resources. Because mineralization of REE and tin (also deemed "critical") are sometimes associated with peralkaline rocks and F-rich A-type granites, respectively, one of the objectives of this study was to evaluate the potential of the rapakivi-associated peralkaline and peraluminous rocks within the Suomenniemi rapakivi granite complex as hosts of pertinent mineralization. This objective was also approached by studying drill core samples provided by the GTK.

Following field work and zircon analyses in 2015–2016, the peralkaline syenitic rocks were suspected to have formed by metasomatism of the rapakivi granites, instead of late peralkaline magmatism. Because of this new hypothesis, the focus of the thesis shifted entirely to the syenitic rocks (henceforth: episyenites or syenitic rocks) of the complex. A common denominator of episyenites is their syenitic mineralogy (i.e. <5 quartz and >65% alkali feldspar) and formation mainly by subsolidus leaching of quartz. Significant mineralization (U, Sn) is sometimes related to these rocks. In recent decades, numerous additions to the English literature

about episyenites have been published and the textural, mineralogical, ore geological variability of these rocks has significantly increased. The episyenite bodies described from the Suomenniemi complex differ from porous and chlorite-bearing episyenites commonly depicted in literature. Thus, two additional objectives were added to the thesis: (1) Characterizing the textural and geochemical changes related to granite–episyenite transformation utilizing mass balance modeling and petrographic analysis; and (2) reviewing the formation processes and mineralization associated with episyenites, worldwide.

3 Methods

The syenitic and granitic rocks of the Suomenniemi complex were originally described by Rämö (1991), with ample field notes and sample material available. Additional fieldwork focused on complementary sampling and detailed mapping of two outcrops of syenitic rocks in the southeastern part of the Suomenniemi complex. These samples formed the core of Paper I. Additional sampling of the syenitic rocks and their granitic host rocks was done from a drill core obtained in 2016 by the GTK from the Kirvesniemi region in Mäntyharju (eastern Suomenniemi complex). The drill core samples formed the core of Paper II. Methods applied to answer the research questions were as follows: (Paper I) U-Pb single grain dating and O-isotope analysis of zircon was performed using secondary ion mass spectrometry (SIMS). Whole-rock Sm-Nd data was obtained by thermal ionization mass spectrometry (TIMS) and laser ablation multi-collector mass spectrometry (LA-ICP-MS). Thin section samples of selected syenitic samples were subject of comprehensive petrographic analysis by polarized light microscopy and cathodoluminescence (CL) microscopy. Electron microprobe was used to analyze the composition of feldspars and mafic phases present in the syenitic rocks and classification diagrams for feldspar, amphibole and pyroxene were constructed using calculated mineral formulae. Geochemical data were obtained for the samples and used in construction of Harker diagrams and chondrite-normalized rare-earth element diagrams. (Paper II) Drill core samples from syenitic rocks, now redefined as episyenites, and their granitic country rocks were analyzed for their chemical composition, and the data were subject to mass balance analysis utilizing the isocon method of Grant (1986). Relevant sections of the drill core were polished and photographed for textural analysis. Thin sections were made of granites and episyenites and subjected to textural and mineralogical analysis using polarized light microscopy and the electron microprobe. (Paper III) Literature survey of the relevant episyenite occurrences and related crustal fluid processes was conducted. Solubility of Si in water and H_2O-Cl fluids was also calculated utilizing the steam tables of the International Association for the Properties of Water and Steam (IAWPS; Wagner et al. 2000) and the solubility model of Akinfiev and Diamond (2009).

3.1 Geochemical data

(Paper I) Hand samples were crushed using a steel jaw crusher and whole-rock powders were prepared using a ball mill with a tungsten carbide bowl. Geochemical data were obtained for ten syenitic samples and three topaz granite samples at the United States Geological Survey. X-ray fluorescence (XRF) spectrometry and inductively coupled plasma mass spectrometry were used to measure major oxides and trace elements, respectively. In addition, ion-selective electrode analysis was used to measure F and Cl

and potassium dichromate titration was used to obtain oxidation state of iron.

(Paper II) Geochemical data was obtained for 25 samples from the Kirvesniemi drill core, including 19 granite samples, five episyenite samples, and one alkali-feldspar granite aplite. Sample powders were prepared from drill core samples using a Mn-steel jaw crusher and a tungsten carbide ball mill. Fused bead samples were made with lithium metaborate tetraborate flux, and concentration of major oxides were measured on a PANalytical Axios mAX 4kW wavelength dispersive XRF spectrometer at the Department of Geosciences and Geography, University of Helsinki. Trace elements and F were measured by an accredited commercial laboratory (Labtium Co., Espoo, Finland) using ICP optical emission spectrometry (Li, Sc, Sr, Y, Zn, Zr), inductively coupled plasma (ICP) mass spectrometry (other trace elements) and ion-selective electrode (ISE) analysis (F). Isocon mass transfer modeling was used to obtain gains and losses of components during metasomatic alteration of granite to episyenite.

3.2 Mass transfer modeling

(Paper II) Geochemical and density data obtained from the Kirvesniemi drill core episyenite and granite samples were used to estimate mass and volume characteristics of high-temperature episyenitization. The isocon method of Grant (1986) was applied in modeling. The results of isocon analysis can be depicted on a C_O vs C_A diagram (isocon diagram), where C_O and C_A are the masses of components in original and altered rocks, respectively. An isocon is a straight line passing through the origin of an isocon diagram and having a slope of one (system mass change = 0), ρ_O/ρ_A (system volume change = 0) or C_O/C_A (mass change of component C = 0). Changes to masses of mobile components can be then calculated according to their position relative to the isocon.

3.3 Whole-rock Sm-Nd and Rb-Sr isotopes

(Paper I) Whole-rock powders made for geochemical analyses were also used for whole-rock Sm-Nd and Rb-Sr analyses. The powders were dissolved in HF-HNO_3, and after evaporation, redissolved in HCl to obtain clear solutions, which were spiked with ^{149}Sm-^{150}Nd and ^{87}Rb-^{84}Sr tracers. Rb, Sr, Sm, and Nd were separated from the sample solutions by chromatographic methods. Isotopic ratios were measured on a VG SECTOR 54 thermal ionization mass spectrometer at the GTK.

3.4 Single-grain zircon U-Pb and O analyses

(Paper I) Zircon separates were obtained from three syenitic samples and two topaz-granite samples using heavy-liquid separation and a Frantz magnetic separator at the GTK. Approximately 50 zircon grains were picked from each sample under a stereo microscope, mounted on epoxy, and polished. Back-scattered electron (BSE) images were taken to choose representative spots for SIMS. Samples were subsequently gold-coated and analyzed using the CAMECA IMS 1280 secondary ion mass spectormeter at the Nordsim laboratory in the Natural History Museum, Stockholm. From each sample, ca. 25 grains were analyzed for U-Pb isotopes and 15 grains were analyzed for O isotopes. The methods followed Whitehouse and Nemchin (2009) for O-isotopes, and Whitehouse et al. (1999) and Whitehouse and Kamber (2004) for U-Pb analyses. U-Pb data were reduced using the Isoplot/Ex software for Microsoft Excel

(Ludwig 2012).

3.5 Field emission scanning electron microscope

(Paper II) Potential carriers of heavy rare earth elements were identified from one episyenite sample using the JEOL JSM-7100F field emission scanning electron microscope (FE-SEM) at the GTK. Running the FE-SEM in high vacuum mode with acceleration voltage of 2 kV and beam current of ca. 1 nA, the carbon-coated thin section sample was scanned for all grains larger than 5 μm and denser than zircon. The FE-SEM was equipped with the Oxford Instruments X-Max energy dispersive spectrometer (EDS), which was used to identify potential carriers of the REE+Y. The FE-SEM was also used to scan four thin sections for hydrothermal monazite for geochronology. No grains large enough for analysis were found and the study was discontinued.

3.6 Electron microprobe analyses

(Paper I) Feldspar, amphibole and pyroxene were analyzed from 15 polished and carbon-coated thin section samples using the JEOL JXA-8600 Superprobe at the University of Helsinki. The analyses were done using a defocused electron beam with a spot diameter of 10 μm, current of 15 nA and acceleration voltage of 15 kV. Natural and synthetic silicate and oxide minerals were used as standards. Amphibole formulae were calculated according to Hawthorne et al. (2012) utilizing the Excel spreadsheet of Locock (2014). The amount of Fe^{3+} in amphibole and pyroxene was calculated by stoichiometry.

(Paper II) Composition of feldspar, amphibole, pyroxene, garnet and Fe-Ti oxides were analyzed from nine polished and carbon-coated thin sections across a syenitic and its immediate granitic margins. The analyses were done using the Cameca SX 100 electron microprobe at the Geological Survey of Finland. Natural and synthetic silicate and oxide minerals were used as standards. Electron beam current was 20 nA and accelerating voltage was 15 kV. The beam diameter was 1 μm for Fe-Ti-oxides, 10 μm for cryptoperthite and, 5 μm for other minerals. Up to six duplicate analyses were made for each data point and average values were used in mineral formula calculations. Analyzed pyroxene were classified according to Morimoto et al. (1988). Amphibole formulae were calculated according to Hawthorne et al. (2012) utilizing the Excel spreadsheet of Locock (2014). Nomenclature of garnet follows Grew et al. (2013).

3.7 Optical and cathodoluminescence petrography

Thin sections made from syenitic samples were subject to petrographic analysis using a polarizing microscope and a hot-cathode cathodoluminescence microscope at the University of Helsinki.

4 Results

4.1 Paper I

Paper I describes the age, origin, mineralogy and chemistry of the syenitic rocks of the Suomenniemi rapakivi granite complex. Isotope geological and geochemical data of several bodies of syenitic rocks and topaz granites within the Suomenniemi rapakivi granite complex is presented.

Macroscopic texture of the syenitic rock was described from hand-samples and relationship of granites and syenitic rocks on outcrop. The syenitic rocks are found as dark red (hematite-stained), irregularly shaped but generally NW-

oriented, dike-like bodies in the southeastern part of the Suomenniemi complex. Despite the several textural varieties of granite in the Suomenniemi complex (porphyritic, coarse and medium-grained), granite is accompanied by a syenitic rock with similar overall texture. Optical petrography, cathodoluminescence microscopy and electron microprobe analysis was used to study the mineralogy and textures of the syenitic rocks. Five mineralogical varieties of syenitic rocks were described:

Type 1: K-feldspar, albite (Ab_{99}) and calcic amphibole. These rocks are characterized by the presence of vugs (in the paper these are called miarolitic cavities, possibly a misnomer) filled with albite, quartz, K-feldspar, epidote, apatite and magnetite. In some samples, magmatic hastingsite is partially altered to ferro-actinolite, whereas in others ferro-ferri-hornblende is the only amphibole present. The feldspar in the rock is fragmented and often highly turbid, containing numerous solid and fluid inclusions. Zircon, apatite, fluorite and calcite are common accessory minerals, and epidote may be present.

Type 2: K-feldspar, albite (~Ab_{99}), sodic amphibole (riebeckite) and aegirine-augite. Some hastingsite is present, but is mostly broken down to aegirine-augite, magnetite and feldspar. Riebeckite is present interstitially and intergrown with aegirine-augite. Magnetite, titanite, apatite zircon, fluorite and calcite are common accessory minerals.

Type 3: K-feldspar, albite (Ab_{99}) and aegirine-augite. Turbid and fractured K-feldspar is overgrown by albite. Aegirine-augite forms granular aggregates and radial overgrowths on rare quartz, as well as some prismatic crystals. Titanite, apatite, hematite and zircon are accessory.

Type 4: Hypersolvus alkali feldspar forming large irregular grains and surrounded by smaller grains that generally display 120° triple junctions. Aegirine-augite is the main ferromagnesian mineral. Titanite, apatite and magnetite are accessory, and riebeckite is present in some samples as inclusions in alkali feldspar or in separate quartz-riebeckite pockets. Albite (Ab_{99}) is present as exsolution lamellae and as swapped rims between alkali feldspar grains.

Type 5: Albite and aegirine-augite or sodian augite and winchitic amphibole. Granoblastic albite (Ab_{99}) surrounds larger albite (Ab_{99}) grains. Titanite and magnetite are accessory.

Cathodoluminescence petrography shows that alkali feldspar (albite and cross-hatched microcline) in the syenitic rocks commonly display red cathodoluminescence color, probably resulting from inclusion of Fe^{3+} in structure of ordered feldspar. Blue luminescence in feldspar may be activated due to formation of electron holes in Al-O-Al bridges, and is thus removed due to feldspar ordering. The hypersolvus variety of feldspar in type-4 syenitic rocks, lacking coarse perthite exsolution, show purple luminescence possibly related to Fe^{3+} within partially ordered alkali feldspar (orthoclase).

Single-grain zircon U-Pb and oxygen isotope data were obtained by SIMS for three syenitic samples (type-3 and type-4) and two topaz granites. Average $^{207}Pb/^{206}Pb$ ages for the syenitic rocks are 1642.2±3.9 Ma to 1644.9±4.6 Ma, and the topaz granites have ages of 1641.3±3.7 Ma and 1635±5.7 Ma (errors at 2σ). Average ages are given due to high mean square weighted deviation (MSWD) values of calculated concordia ages; for one syenitic sample an acceptable concordia age of 1646.2±3.9 Ma (MSWD = 1.4) was obtained. Average $\delta^{18}O_{VSMOW}$ values are 8.04±0.18‰ to 8.26±0.17‰ for syenitic rocks and 7.79±0.17‰ and 8.03±0.17‰ for the topaz granites. Inter-sample variation was notable in some samples (e.g. from 6.88 to 8.58‰ in syenitic sample

A1164).

Whole-rock Sm-Nd and Rb-Sr data were obtained by TIMS for one syenitic sample (+one duplicate) and two topaz granite samples (A1097 and A1097-GREGR, the latter being a greisenized topaz-granite variety). Initial Sm-Nd values (εNd_i) of the samples were calculated at the emplacement age of the rapakivi granites (1644 Ma; Rämö and Mänttäri 2015), being -1.9 and -1.6 for the syenitic samples and -2.9 (A1097) and -1.0 (A1097-GREGR) for the topaz granites. Whole-rock εSr(1644 Ma) values for the two duplicate analyses of the episyenite sample are -69.9 and +11.1.

Geochemical analyses were obtained for twelve syenitic rocks and three topaz granites. Major oxides, trace elements and Fe^{3+}/Fe^{2+} ratios were analyzed. These data were compared to the data from Rämö (1991). The data show that compared to the granites of the Suomenniemi complex, the syenites are enriched in total alkalis, Na_2O, Al_2O_3 and depleted in SiO_2, as expected from their albite-rich and quartz-poor mineralogy. K_2O is either enriched or in the range displayed by the granites, but significantly depleted in the type-5 albite syenites. The trace elements Zn, Zr, Rb and Sr show no trends relative to SiO_2. Fe^{3+}/Fe^{2+} ratios are significantly larger in the syenitic rocks compared to the granites. REE concentrations are in the range displayed by the granites of the complex.

The most important inferences from these results are:

1. The textures of syenitic rocks and their host granite are comparable, even though the texture of the granite varies between outcrops.
2. The rocks show mineralogical and textural similarities to fenites and episyenites, including replacement of quartz by aegirine-augite.
3. Activation of red cathodoluminescence in K-feldspar imply interaction of feldspar with an oxidizing fluid.
4. Age and O-isotope values of zircon in syenitic rocks are indistinguishable from values presented for granites of the complex.

Paper I presents an original hypothesis of the formation of the syenitic rocks by post-magmatic hydrothermal de-quartzification (episyenitization) and alkali metasomatism of the rapakivi granites. Thus, the initial hypothesis of their magmatic origin and igneous relationship with the rapakivi granite magmas was discarded, and the syenitic rocks are re-defined as episyenites. Infiltration of high-temperature fluids along NW-oriented zones of weakness in the granites resulted in quartz dissolution, breakdown or replacement of feldspar and amphibole and formation of relatively sodic and oxidized mineral assemblages. The source of the fluids is unknown; the mineralogical and textural similarities with fenites and Suomenniemi episyenites suggest the possibility of an alkaline magma body beneath the present erosion surface. Ambiguous microtextures (magmatic or metasomatic) and the necessary high temperatures required for the formation of hypersolvus feldspar in the type-4 episyenites suggest high-temperature magmatic fluids were integral in the formation of these rocks.

4.2 Paper II

The second paper presents a mass balance model for formation of some of the episyenite bodies and discusses textural relationship between granite and episyenite. The work is based on a 150 m diamond-drill core supplied by the GTK. The drill core comprises mainly green or pink amphibole or amphibole-fayalite granite. A biotite granite dike cuts the amphibole granite, and some cataclastic fracturing associated with quartz veining is present in the amphibole

granite. Two episyenite bodies with differing mineralogy were discovered in the drill core: (1) Syenitic, with hypersolvus feldspar, plagioclase, hedenbergite–sodian augite; and (2) quartz alkali-feldspar syenitic, with hypersolvus feldspar, minor plagioclase, aegirine-augite. The second body is cut in the middle by a ca. 30 cm alkali granite aplite, comprising albite and quartz. These rock types are similar to type-4 rocks described in Paper I, but differ due to presence of plagioclase (1,2), >5% quartz (2) and augite–hedenbergite instead of aegirine-augite (1).

The transition of granite to syenitic episyenite (1) was examined from the drill core. The transition is gradual and marked by granoblastic recrystallization of plagioclase and K-feldspar. Formation of Fe-rich augite or hedenbergite, magnetite and titanite possibly resulted from breakdown of amphibole and biotite. Fluorite is a notable accessory in the marginal zone. K-feldspar displays Na-enrichment both in the episyenitic facies and in its granitic margin.

Whole-rock geochemical analyses of the rocks show enrichment of Al, Na, and depletion of Si in the episyenites relative to the granites. Ca is depleted and Mg is enriched in the quartz-bearing episyenite. Increase in HREE in the fluorite-rich section of the syenitic episyenite is also noticeable, albeit not significant from the ore-geological point of view. It is also noted that some trace elements (Zr, Nb) display significant variation in the granites, and these elements cannot be used in mass balance calculations. This observation underlines the importance of careful examination of protolith composition, especially where trace elements are considered.

Mass balance calculations based on immobility of Al suggest a significant volume and mass loss (up to 20% volume loss due to quartz dissolution and SiO_2 transport) from the episyenites, implying leaching has been the primary reason for quartz-depletion instead of replacement. The syenitic or quartz-syenitic rocks described have features suggesting high-temperature deformation and lack cavities shaped after quartz dissolution. As leaching of quartz is hindered in ductile shear zones due to low permeability, a quartz-depletion step in brittle conditions may have taken place prior to ductile deformation.

The immobility of Al, while common conclusion or in crustal metasomatism, is not necessarily valid. While Al is commonly considered immobile in crustal fluids due to its low solubility in water, Al solubility may be increased in Na-bearing solutions relative to pure water. If Al-immobile model is discarded, and zero volume change is assumed instead, up to 8 g SiO_2 per 100 g of rock has been removed, and 3.5 g of Al_2O_3 has been added, along with lesser additions of Na_2O and other major oxides. However, Na-enrichment is the only change seen in the immediate granitic wall rocks of the episyenites, which implies fluid that interacted with the granites was essentially a NaCl-H_2O-fluid and lacked significant Al. Still, the SiO_2 losses calculated assuming immobile Al can be treated as upper limits.

While hypersolvus feldspar requires high formation temperature (>650°C), it could theoretically form in the subsolidus in the epizonal, low-pressure setting of the Suomenniemi complex. Yet, the high apparent temperatures and ambiguous textures warranted for discussion about the possible magmatic (intrusive) origin for these rocks. It was concluded that, while the origin of these rocks remains ambiguous, it is possible that these high-temperature episyenites formed in the subsolidus via interaction of the Suomenniemi granites with a sodic fluid,

possibly during multiple stages. Emplacement of the Suomenniemi rapakivi granite complex was followed by several magmatic episodes in the area, including the emplacement of SW-striking diabase dikes and ultimately the emplacement of the massive Wiborg rapakivi granite batholith to the south. The brittle–ductile deformation and fluid infiltration resulting in the formation of these episyenites may have been related to these magmatic episodes in the 15 m.y. following the emplacement of the Suomenniemi complex granites.

4.3 Paper III

Paper III discusses characteristics, formation conditions and potential mineralization of episyenites. Episyenites are rocks formed by dissolution of quartz from granites or migmatites during events of concentrated upper crustal fluid flow. Quartz is typically leached, leaving behind a vuggy feldspathic husk that may be filled with hydrothermal minerals. Extension of episyenitization over lithological boundaries along with the preservation of magmatic textural characteristics (e.g. shapes of primary feldspar) of the protolith are major diagnostic features of an episyenite. Alkali-metasomatism is characteristic of the process and episyenites tend to include large amounts of secondary albite and/or K-feldspar. Primary mafic minerals are typically leached or replaced, and chlorite is the main Fe-Mg-mineral present. Some episyenites include mafic minerals typical of fenites or skarns, including clinopyroxene. Due to their high permeability, episyenites may have experienced multiple hydrothermal episodes, evident by superimposed alteration assemblages (e.g. K-feldspar, micas, clays) and assemblages of vug-filling minerals (e.g. quartz, muscovite, calcite and U, Sn or Au ore). Ore mineralization in some episyenites, especially within the U-rich Variscan granites of central Europe, is an important consequence of formation of vuggy episyenites; those being essentially sinks for metal deposition.

Quartz can be removed due to leaching (i.e. quartz dissolution and Si-transport by fluid advection), consumption in metasomatic reactions, or quartz vein segregation. As crustal fluids tend to be Si-saturated, the most important question in formation of vuggy, quartz-free episyenites is the mechanism promoting quartz leaching. Solubility of Si in crustal fluids can be increased by either lowering temperature within the retrograde Si solubility field (20–90 MPa and 350–500°C), or increasing temperature and/or pressure outside the retrograde conditions. Increase in fluid salinity may have a minor effect in Si solubility. Crustal permeability plays a large role in whether episyenites can form. In a ductile shear zone, permeability is low, which limits the possibility of flux of Si-undersaturated fluid and long-distance Si-transport. The loss of quartz in these conditions may result from replacement, or dissolution resulting from, e.g. fluctuation of pore fluid pressure, which results in the formation of hydrothermal quartz veins. In contrast, brittle shear zones and joints can facilitate extensive fluid fluxes and Si-transport over long distances. Fast drop in temperature in hydrostatically pressurized hydrothermal circulation cells above upper crustal intrusions is the most likely process to cause leaching of quartz. Solubility calculations imply that complete loss of quartz from a granite requires high fluid-rock ratios in the order of 10^2–10^3 in these conditions.

While most episyenites form along subvertical shear zones and joints in the upper crust undergoing extension, one example of episyenite in compressional setting has been described from the Mont Blanc Massif (French–

Italian Alps). In that case, episyenites are related to opening of fractures between mid-crustal brittle–ductile shear zones, and formation of segregation quartz vein. Although Si-depleted selvages around orogenic quartz veins are not typically considered episyenites, the preservation of porosity and secondary mineral assemblage consisting of albite, adularia and chlorite make these Mont Blanc rocks very similar to episyenites from upper crustal environments.

Magmatism is likely important driver of crustal fluid circulation, producing the necessary temperature anomalies in the upper crust and thus making retrograde quartz dissolution feasible process in the upper crust. Fluid inclusion and stable isotope studies suggest that meteoric, magmatic, metamorphic fluids and basin formation waters, as well as mixtures thereof, may be responsible for episyenitization. As the influx of magmatic fluids to hydrothermal circulation cells is small compared to meteoric fluids, the latter are likely to be vastly more important than magmatic fluids in episyenite formation. In addition, the importance of magmatic fluids may be overestimated if O-isotopes are used to estimate fluid sources, as the O-isotope composition of deep crustal fluids tend to be buffered by the composition of the country rock.

Coeval or later magmatism spatially connected to the episyenitized structures may result in crustal shearing and temperature increase causing collapse and deformation of the porous episyenites. Deformed and weakly porous episyenites may be hard to recognize as episyenites; such rocks may be more common than currently considered.

While the importance of magmatic fluids may be overestimated in episyenitization, they may be important in formation of Sn deposits in episyenites related to epizonal A-type granite intrusions. In these systems, primary Sn enrichment results in concentration to this element in late magmatic fluids, the cooling of which leads to precipitation of cassiterite in episyenite cavities. U-deposits in episyenites are more likely related to circulation of oxidized meteoric fluids through U-rich felsic rocks, followed by precipitation of U-minerals in episyenite cavities. Gold mineralization in episyenites is rare and may be related to an unusual metamorphic fluid association. Rare earth element mineralization, also rarely present in episyenites, may be related to input of REE-rich fluid, possibly originating from alkaline or carbonatite magmas.

5 Discussion

5.1 On episyenites and their classification

Many episyenites described in literature are similar to those discussed in the classic review of episyenites from the French Massif Central by Cathelineau (1986), entitled ”The hydrothermal alkali metasomatism effects on granitic rocks: Quartz dissolution and related subsolidus changes”. The title of this review may lead to misinterpretation of the process of episyenite formation, as quartz dissolution is not the result of alkali metasomatism, which may both precede and succeed quartz loss. Although it is understandable that alkali metasomatism is nearly ubiquitous in episyenites, as alkalis (especially Na) are a significant component of deep crustal fluids, a fluid does not need to be particularly alkali-rich to dissolve quartz, and alkalis only slightly increase Si solubility in water (e.g. Akinfiev and Diamond 2009). Other features mentioned in this review, such as macroscopic porosity or chloritization do not characterize all rocks named episyenites (e.g. Paper I; Caballero 1993; Charoy and Pollard

1989; Recio et al. 1997), as discussed in Paper III. Although the common case of episyenitization by quartz leaching leaves behind a characteristic, vuggy feldspathic husk, the vugs may be filled with hydrothermal minerals or collapse due to deformation, and preservation of porosity cannot be used as a definitive characteristic of an episyenite. In addition, at high metasomatic temperatures (Caballero 1993) or due to saline fluids, possibly similar to fenitizing solutions (Preston et al. 2003), pyroxene or amphibole may form instead of chlorite (e.g. Cuney et al. 2012).

At their core, episyenites are alkali-feldspar-rich rocks formed by hydrothermal quartz-depletion. However, other than by these very broad strokes, episyenites are diverse rocks, and defining the term episyenite is challenging. Rocks are typically assigned a name based on mineralogy and their primary formation process (e.g. magmatism, metamorphism). If episyenite is defined as the term used in literature, viz., a quartz depleted rock of syenitic composition (i.e. >65% alkali feldspar and <5% quartz), rocks would be classified episyenites by what the rock does not have (quartz), and the mineralogy of the protolith would have to be known. This common definition, also adopted in this contribution, could also include rocks not typically considered episyenites, such as albitites, some fenites, and quartz-depleted selvages of orogenic quartz veins. In addition, quartz can be depleted from a rock in several ways, including leaching (i.e. diffusion + advection), metasomatic replacement, or diffusion; could all these mechanisms be considered episyenitization? These problems suggest that the nomenclature of metasomatic rocks is due for an overhaul and some future collective effort should be directed to constrain the term episyenite.

5.2 Open research questions and reliability of results

As many scientific studies, this thesis answers a few questions while opening many more. The episyenites studied are situated along a NW-oriented zone in the eastern side of the Suomenniemi rapakivi granite complex. Additional field studies would ascertain whether the metasomatism has affected Svecofennian rocks outside the complex. Episyenites potentially formed within the Svecofennian leucogranites and migmatites may show different mineralogy and ore-forming potential (e.g. U-mineralization in episyenites is connected to their occurrence within U-rich leucogranites) and give further implications for the formation conditions of these episyenites and may clarify the open questions surrounding the high-temperature varieties. In addition, the timing of alteration is important to ascertain the relationship of the syenitic rocks with the Suomenniemi magmatism. U-Pb dating of zircon (Paper I) already shows that the zircon in the episyenites is indistinguishable from the zircon in the granites of the Suomenniemi complex. With appropriate sampling, U-Pb analysis of secondary monazite or xenotime should be possible, giving additional information about the formation history of the rocks.

In addition, several other aspects of the syenitic rocks could provide worthwhile research paths, including the many natural examples of dissolution-reprecipitation (Paper I), formation of green granite (described in Paper II), cathodoluminescence activators, and the mass-volume characteristics of most episyenite types (Paper I). In addition, the discussion of Paper II raises important questions about the validity of the mass transfer model presented and the origin of the high-temperature syenitic rocks of the Suomenniemi complex. Specifically, a possible late-magmatic origin for the high-temperature

syenitic rocks, or significant hydrothermal input of Al, could invalidate the model and conclusions of Paper II, thus calling for additional discussion, presented below.

5.3 Input of Aluminum

The results of the mass balance analysis of the "type-4" episyenites in Paper II suggest up to 20% volume decrease resulting from dissolution of quartz. The high-temperature alkali feldspar composition and plastic (granoblastic) recrystallization feldspar in these rocks suggest that permeability of the episyenite bodies has been low, comparable to a ductile shear zone. In such a case, retrograde quartz dissolution is not possible and low time-integrated flux prevents leaching of quartz. If Si dissolves due to, e.g., fluctuation of fluid pressure in a mainly ductile environment, the dissolved Si would not be transported far from its source and significant quartz veining should be observed. The only way to leach quartz efficiently in a ductile shear zone is the unlikely event of fluid flow along an up-temperature gradient. Because of the lack of quartz veining and measured volume characteristics, brittle-to-ductile evolution was suggested for the episyenites in Paper II. However, if Al was indeed added in significant amounts, the required volume change would have been significantly smaller than estimated. Zero volume change model for the syenitic episyenite requires addition of ~3 g Al_2O_3 / 100 g of rock, and loss of ~7 g of SiO_2. If this amount of quartz segregated into a vein, a one-meter-wide episyenite body should be associated with a quartz vein ~10cm in width. Minor quartz-enrichment is seen in the marginal zone of the syenitic episyenite body observed in the drill core studied in Paper II but is not nearly enough to explain the amount of Si apparently removed from the episyenite, and thus some quartz leaching is required in any case.

The solubility of Al is increased in Na-bearing solutions relative to pure water (Walther 2001). For example, at 500°C in a 0.5 m NaCl solution (e.g. seawater) ~0.05 wt.% of Al_2O_3 can be present. Cooling of a 0.5 m NaCl solution from 500 to 400°C decreases Al solubility from ~0.05 wt.% to ~0.025 wt.%. Thus, retrograde quartz dissolution (or fluid flow along a down-temperature gradient in general) may be associated with concomitant input of Al, whereas prograde quartz dissolution may be associated with loss of Al. Some input of Al is thus possible, or even likely, and the volume loss percentages suggested by the mass transfer models (Paper II) should be treated as upper limits.

Preston et al. (2003) showed that fenitizing solutions may have, among other components (such as Fe, Mg), high amounts of dissolved Al or Si, far exceeding the estimated solubility of Al or Si in crustal fluids. Such supersaturated fluids (approaching hydrous melts) can cause extensive metasomatism and growth of hydrothermal minerals, and thus fenites have often undergone complete metasomatic transformation and are associated with veins rich in sodic pyroxene or amphibole. Such fenitizing solution could result in the formation of riebeckite in the type-4 episyenites, although formation of minerals characteristic to fenites do not necessarily imply an carbonatite–ijolite source for the fluids (e.g. Cuney et al. 2012). The formation of aegirine-augite veinlets in type-3 episyenites and riebeckite veinlets in type-2 episyenites also show that the fluid present contained high amounts of components other than Na. Geochemical modeling could be used to study whether these components were mainly derived from the metasomatizing granite or from

external sources.

5.4 Alternative genetic theories

The syenitic rocks found in the Suomenniemi complex are described using igneous terminology in Paper I, but later concluded to be episyenites, some of which underwent "fenitization-style alteration". These apparent contradicting descriptions mirror the confusion surrounding the origin of these rocks. The type-1 episyenites in Paper I are typical barren episyenites with numerous close analogues, such as episyenites within the Bohus granite, SW Sweden (Petersson and Eliasson 1997). Even these type-1 rocks, however, have amphibole instead of chlorite, possibly implying higher temperatures than many (but not all) episyenites. The type-2 to type-4 episyenites have textural and mineralogical similarities with episyenites (Cuney et al. 2012), fenites (Le Bas 1987) and peralkaline igneous syenites (Andersen 1984), whereas type-5 episyenites are similar to metasomatic albitites (e.g. Albino 1995). Most problematic are the type-4 rocks that include hypersolvus feldspar, implying high (possibly magmatic) temperatures. While metasomatic hypersolvus alkali feldspar is common in high-temperature fenite aureoles, its formation in the subsolidus in dike- or pod-like episyenite bodies is questionable.

The aplite described in Paper I (fig. 2a) could have major significance in understanding the post-magmatic origin of these type-4 rocks. The 3-cm-wide aplite cuts both the granite and the syenitic rock; it is relatively quartz-poor and clinopyroxene-bearing within the syenitic rock, which implies that the aplite was formed before metasomatism. However, compositional differences in the aplite could possibly be explained also if the type-4 syenitic rocks are magmatic, and granite and syenite magmas co-existed; in this case, the aplite formed due to fracturing of a highly crystalline magma.

Paper III discusses possible mechanisms of quartz dissolution in episyenites and concludes that long-lived brittle conditions (at temperature <575°C if the onset of retrograde quartz dissolution is the limiting factor) are necessary for complete removal of quartz in episyenites, especially if they are not associated with segregation quartz veins or quartz replacement. Due to this problem, it was suggested in Paper II that an early brittle stage (which led to quartz dissolution) was followed by a high-temperature ductile deformation stage, which is a rather unintuitive model. Paper II also discusses the possibility of magmatic origin for the hypersolvus feldspar –containing type-4 rocks. Although Paper II ultimately opts for a post-magmatic origin, the data presented leaves room for alternative interpretations. For example, it is not certain that the hypersolvus feldspar did not form already in the magmatic stage, or that quartz was removed in a post-magmatic stage.

The discussed models of formation for the hypersolvus feldspar –bearing rocks in Paper II (i.e. subsolidus episyenitization or magmatic dike intrusion) do not explain all the observed characteristics of these rocks. Textural relationship between the granite and syenitic rocks imply that if the syenitic rocks are magmatic, a syenite magma must have coexisted with a granite magma, and the former evolved from the latter. A third model can be created, being a combination of the two discussed models: Magmatic shearing event at low (<0.4) melt fraction and >650°C (possibly >770°C) resulted in fluid exsolution and removal of interstitial, Si-rich melt along the shear and into the surrounding magma, resulting in accumulation and recrystallization of feldspar in magmatic shear zones. Although

co-magmatic deformation is well documented in syntectonic plutons (Zibra et al. 2012), it is understandably less significant in anorogenic setting. The shearing of the magma body, which at that point was rigid and comprised mainly alkali feldspar and plagioclase, could have been caused by uplifting related to intrusion of magma below the southeastern part of the Suomenniemi complex. In this model, the high recrystallization temperatures are not unreasonable and significant dissolution of quartz is not required. Albitite formation (i.e. type-5 episyenites) related to such process is related to extensive Na-metasomatism along the marginal zone of some of these dehydrated zones.

Obviously, if this magmatic shearing model is correct the mass balance calculations from Paper II are not valid. Instead, mass and volume loss would have been even greater than the maximum limit of 20% given in Paper II to explain the loss of Al with the interstitial Si-rich melt. Modeling the evolution of rapakivi magma (e.g. rhyolite-MELTS; Gualda et al. 2012) could give composition of interstitial magmas at different melt fractions, which can be then compared to mass transfer models. Of course, modeling may not produce accurate results due to the cumulate nature of the rapakivi granite (Rämö 1991). Input of Na by fluids is necessary for the formation of these rocks, as shown by mass transfer modeling. In addition, the observed minerals suggest relatively oxidizing conditions (e.g. titanite and magnetite instead of ilmenite) that could also be explained by fluid channeling. The swapped albite rims (Paper I and II) that surround K-feldspar may also require the presence of a sodic fluid. Whether this third model is realistic or not depends on whether channeling of fluid in a magmatic shear zone is possible. Fluid can move in an intrusion as bubbles rising due to their buoyancy, together with moving magma or along porous networks. Permeability of a magmatic shear zone could be increased by fracturing of the magma and/or as deformation assists coalescence of gas bubbles (Sparks 2003). Just like the episyenitization model, were this magmatic shearing model accurate, it would have an impact on how we observe these kinds of mesoscopic heterogeneities in A-type granite plutons. Syenitic "dikes" in granite are not necessarily intrusive features, rather than formed in situ due to shearing, fluid channeling, and recrystallization.

The process considered above would mean that the type-4 syenitic rocks are not episyenites (as that term should be preserved for subsolidus rocks) but this would not necessarily apply to the other types described in Paper I. The type-1 rocks are likely formed via subsolidus quartz leaching and replacement, as shown by prevalence of brittle deformation and similarities with episyenites described in literature, and thus probably formed after the transition from a lithostatically to hydrostatically pressurized hydrothermal system. The type-2 rocks, having granoblastic, deformed quartz and igneous calcic amphibole in addition to fragmented K-feldspar and albitized plagioclase, have also likely been deformed in the subsolidus or at very low melt fractions. The type-3 rocks are fenite-like and possibly formed mainly by replacement of quartz and alkali metasomatism. Thus, these type-1–3 rocks can probably be called episyenites, but additional mass transfer modeling would be useful in ascertaining their assumed near-isovolumetric formation.

6 Conclusions

The Suomenniemi rapakivi granite complex contains small amounts of syenitic rocks, proposed to have formed by dissolution of magmatic quartz and sodic metasomatism due to interaction of the rapakivi granites with sodic hydrothermal solutions. The diverse mineralogy and texture of the syenitic rocks, reclassified as episyenites in this contribution, record varying thermal and chemical conditions. Some types record brittle deformation and contain the low-temperature paragenesis albite and microcline, whereas a high-temperature variety shows formation and ductile deformation of hypersolvus feldspar at >650°C, and is in some places associated with granoblastic albitite. U-Pb and O-isotopic data obtained from zircon in the syenitic rocks show that this zircon is identical to zircon in the granites; the transitional contacts between rapakivi granite and the syenitic rocks also show the intimate connection between rapakivi granite and the syenitic rocks. While some varieties can be named episyenites with good certainty on textural basis alone, some aegirine-augite and/or hypersolvus feldspar – bearing bodies are also reminiscent of fenites and igneous syenites. High-temperature sodic metasomatism suggests a magmatic fluid source, possibly connected to the anorogenic magmatic events during, and in the 15 m.y. following the emplacement of the Suomenniemi complex at ca. 1644 Ma. The ductile deformation observed in some rocks also likely formed during this time. Despite the minor REE enrichment relative to the Suomenniemi granites in some episyenite samples, the Suomenniemi episyenites do not display significant potential to host important mineralization.

Episyenites are alkali-feldspar rich rocks formed primarily by hydrothermal leaching of quartz in hydrostatically pressurized hydrothermal systems above cooling intrusions in the upper crust. At conditions in which feldspar behaves in ductile manner, leaching is difficult, and quartz dissolution tends to result in local growth of hydrothermal or metasomatic minerals (including quartz). Nevertheless, mass balance analysis of those syenitic rocks of the Suomenniemi complex that were deformed in ductile manner suggest that significant loss of SiO_2 due to leaching of quartz occurred; brittle-to-ductile evolution (episyenitization followed by heating and ductile shearing) was suggested for formation of these rocks. Due to the unintuitive nature of this model, a magmatic genetic model was also constructed, suggesting deformation of magma at low melt fractions, which formed relatively permeable dike-like bodies in situ, thus preserving some textural features of the rapakivi granite. In this model, late interstitial Si-rich melt was pushed out leading to feldspar accumulation and ductile deformation, and significant quartz dissolution was not required. This hypothetical model is only applicable to the high-temperature hypersolvus syenitic rocks of the Suomenniemi complex, whereas the other syenitic rocks are likely formed in the subsolidus due to fenitization-style replacement and quartz leaching (episyenitization) after the consolidation of the Suomenniemi complex.

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